9th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 18–22, 2001

Noise properties of iron-filled carbon nanotubes

S. Roumiantsev[a]†, R. Vajtai‡, N. Pala†, B. Q. Wei‡, M. S. Shur†,
L. B. Kish§ and P. M. Ajayan‡

† Department of Electrical, Computer and Systems Engineering,
Rensselaer Polytechnic Institute, Troy, New York 12180-3590, U.S.A.
‡ Department of Materials Science and Engineering,
Rensselaer Polytechnic Institute, Troy, New York 12180-3590, U.S.A.
§ Department of Materials Science, The Ångström Laboratory,
Uppsala University, P.O.B. 534, S-75121, Uppsala, Sweden
[a] Ioffe Physico-Technical Institute, St Petersburg, Russia

Abstract. Extraordinary mechanical and electronic properties of carbon nanotubes have attracted great interest. In this talk we describe electrical and noise properties of iron-filled multi-walled nanotubes. Our results show that these nanotubes have unusual current dependence of noise and exhibit a much smaller noise than single-walled nanotubes.

Introduction

Carbon nanotubes have many unique properties that attracted the attention of microelectronics and nanotechnology communities. For example, the mechanical strength and thermal conductivity are higher than these values for diamond and boron nitride [1, 2]. Also, different types of nanotubes (single-walled tubes with varied chirality, multi-walled tubes) have different properties ranging from metallic to semiconducting behavior [1], and exhibiting different effects, such as ballistic electron transport [3] and Aharonov–Bohm oscillations [4].

Filling nanotubes with metals and semiconductors[5], inducing defects in their structure [6], producing "Y" shape tubes [7] or "decorating" them with functional groups covalently attached to their walls cause further variations of their widely varied electronic properties. These modified tubes might be used for building simple devices in individual nanotubes [8].

Low frequency noise analysis is an effective tool for device and material characterization. In many cases, noise is more sensitive to existing disorder, nonlinear behavior or contact problems in the device than dc measurements. Moreover, $1/f$ noise can be used as a diagnostic tool for quality and reliability assessment of electronic devices [9, 10].

On the other hand, the level of the low frequency noise is one of the most important characteristics of electronic devices, which determines whether the devices are suitable for practical microwave and optical systems [11]. So far, the results of the noise measurements on nanotubes are only available for single-walled nanotubes [12]. In this paper, we will present the results of the $1/f$ noise measurements for multi-walled, partially iron-filled nanotubes and demonstrate that these nanotubes have unusual current dependence of noise and exhibit a much smaller noise than single-walled nanotubes.

1. Experimental details

Carbon nanotubes used in our measurements were produced by chemical vapor deposition from xylene and ferrocene [13]. We applied a mixture of the two precursors resulting

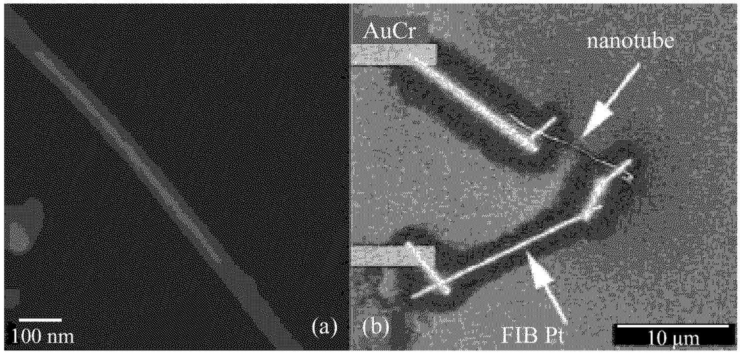

Fig. 1. (a) FE-SEM micrograph of a multi-walled nanotube filled partially with iron, (b) FE-SEM micrograph of the nanotube with FIB interconnects.

1:10 Fe/C atomic ratio in the reaction zone and near entire iron cores in growth nanotubes. As can be seen from Fig. 1(a), the nanotubes were only partially filled with iron. In order to perform dc and noise measurements on individual tubes, the samples were prepared as follows. First, the silicon wafer was thermally oxidized (resulting in 300 nm thick SiO_2 layer) and a metal (Au/Cr) electrode pattern was prepared using conventional lithography technique. In the next step the nanotubes were sprayed onto the SiO_2 surface as a low-density nanotube film, in which most of the tubes were separated from each other. Individual tubes with optimal location and shape were selected by FE-SEM microscopy. Focused Ion Beam (FIB) technique was used in order to deposit platinum interconnections and make contacts to the nanotubes (see Fig. 1(b)). The time and current of FIB preparation was minimized to avoid excessive ion irradiation of nanotubes and substrate.

The low frequency noise was measured in two contacts configuration in the frequency range from 1 Hz to 3 kHz at room temperature. The voltage fluctuations S_V from 2 kΩ resistor connected in series with the structures under test were measured by SR 770 Network Analyzer.

2. Results and discussion

Current voltage measurements showed that nanotubes had ohmic behavior under the dc bias from −4 to 4 V with resistance of ~20 to 60 kΩ.

The noise spectra of the short circuit current fluctuations had the form $S_I \sim 1/f^{\beta}$ where β is close to unity. This $1/f$-like spectrum is very common for many semiconductor devices and materials and was also recently observed in single-walled nanotubes [12].

However, the current dependence of noise was quite different from that reported in [12] and from what is typical for linear metal and semiconductor resistors. In contrast to typical dependence of the spectral noise density $S_I \sim I^2$ (I is the current), we found $S_I \sim I^{\alpha}$ with $\alpha < 2$ (from 1 to 1.5 for different samples). This behavior indicates a current dependence in the number, amplitude or rate of elementary fluctuators or in the coupling strength if the effect is a cooperative (nonlinear) one. This unusual (for a linear region of the I–V characteristic) dependence might indicate that the noise could be generated by a small non-linear contact resistance at the points of the contacts of FIB metal to the nanotube. If in the contact resistor, the number of elementary fluctuators is proportional to the current (like in silicon diodes), a similar $S_I \sim I$ dependence can be expected [14].

In order to estimate role of the interconnects we also measured the noise of the test structure consisted from a simple FIB stripe. We found the conventional $S_I \sim I^2$ behavior

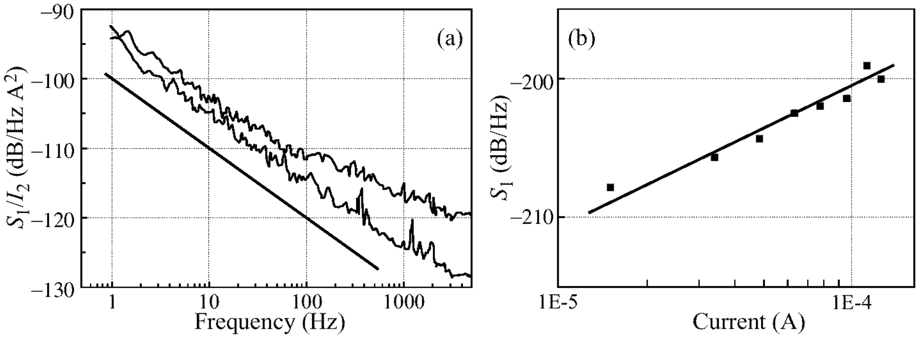

Fig. 2. Frequency (a) and current (b) dependencies of spectral noise density of current fluctuations for iron-filled multi-walled nanotubes. The applied dc voltage was 1 V and 4 V for the upper and lower spectrum, respectively, in part (a), and the frequency was 200 Hz for values displayed in part (b).

for the test structure.

At current $I = 10^{-5}–10^{-4}$ A the relative spectral noise density of current fluctuations in iron-filled multi-walled nanotubes was much smaller than that reported in Ref. [12].

Acknowledgements

This work at Rensselaer was partially supported under the DARPA Molecular Level Printing Program (Grant # N66001-98-1-8917). R. Vajtai's work is supported by the North Atlantic Treaty Organization (NATO) under a Grant awarded in 2000, (No. 0075178). L. B. Kish's work is supported by NFR, Sweden.

References

[1] R. Saito, G. Dresselhaus and M. S. Dresselhaus, *Physical Properties of Carbon Nanotubes* (Imperial College Press, London, 1998).
[2] P. M. Ajayan and T. W. Ebbesen, *Rep. Prog. Phys.* **60**, 1025 (1997).
[3] C. T. White and T. N. Todorov, *Nature* **393**, 240 (1998).
[4] A. Bachtold, et al. *Nature* **397**, 673 (1999).
[5] P. M. Ajayan and I. S. Iijima, *Nature* **361**, 333 (1993).
[6] B. Q. Wei, et al. under publication
[7] C. Papadopoulos, A. Rakitin, J. Li, A. S. Vedeneev and J. M. Xu, *Phys. Rev. Lett.* **85**, 3476 (2000).
[8] C. W. Zhou, J. Kong, E. Yenilmez and H.J. Dai, *Science* **290**, 1552 (2000).
[9] F. Otten, L. B. Kish, C.-G. Granqvist, L. K. J. Vandamme, R. Vajtai, F. E. Kruis and H. Fissan, *Appl. Phys. Lett.* **77**, 3421 (2000).
[10] C. Pennetta, L. B. Kiss, Z. Gingl and L. Reggiani, *J. Nanoparticle Res.* **2**, 97 (2000).
[11] M. J. Buckingham, *Noise in electronic devices and systems*, 1983.
[12] P. G. Collins, M. S. Fuhrer and A. Zettl, *Appl. Phys. Lett.* **76**, 894 (2000).
[13] B. Q. Wei, Z. J. Zhang, G. Ramanath and P. M. Ajayan, *Appl. Phys. Lett.* **77**, 2985 (2000).
[14] L. B. Kiss and T. G. M. Kleinpenning, *Physica B.* **145**, 185 (1987).